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# A Foil Thrust Bearing Test Rig for Evaluation of High Temperature Performance and Durability

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**14. ABSTRACT**
A new test rig is designed to evaluate the start-stop cyclic durability of high-temperature solid lubricant coatings applied to foil thrust bearing systems. This test rig also allows the characterization of low speed thrust bearing performance, augmenting existing high speed test capabilities. The Low-Speed Thrust Bearing Rig is designed to test foil thrust bearings at speeds up to 21,000 rpm and temperatures up to 540 °C (1000 °F), with variable thrust loads. Thrust bearings can be subjected to tens of thousands of start-stop cycles to simulate decades of service in a turbomachinery application. Initial testing has validated the rig capabilities by subjecting a bearing and thrust runner to more than two thousand start/stop cycles at a temperature of 430 °C (800 °F).

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## Introduction

Foil gas bearings operate by generating a self-acting gas film between surfaces in relative motion. A converging gap in the direction of rotation compresses a gaseous lubricant to elevated pressure, separating the relatively moving surfaces and providing a load-carrying capacity. The use of the surrounding process gas as the bearing lubricant eliminates the need for an auxiliary lubrication system to deliver conventional oil lubricants. This enables drastic reductions in weight, complexity, and maintenance costs of foil bearing-supported turbomachines as compared to rolling element bearing-supported counterparts. It also permits higher shaft speeds by removing the DN speed limits inherent to rolling element bearings.

Oil-free turbomachines generally require both journal and thrust foil bearings to support the shaft in radial and axial directions, respectively, with these two types of bearings having different geometry. A typical foil journal bearing consists of a compliant top foil that provides a boundary for the hydrodynamic gas film, a combination of compliant support foils often formed into strips of corrugated bumps, and a rigid outer shell within which the foils are mounted (figure 1). The radial compliance of the bearing provides tolerance to shaft misalignment, shock loading, centrifugal and thermal distortion, and other component- or system-level phenomena that would overload rigid bearings.

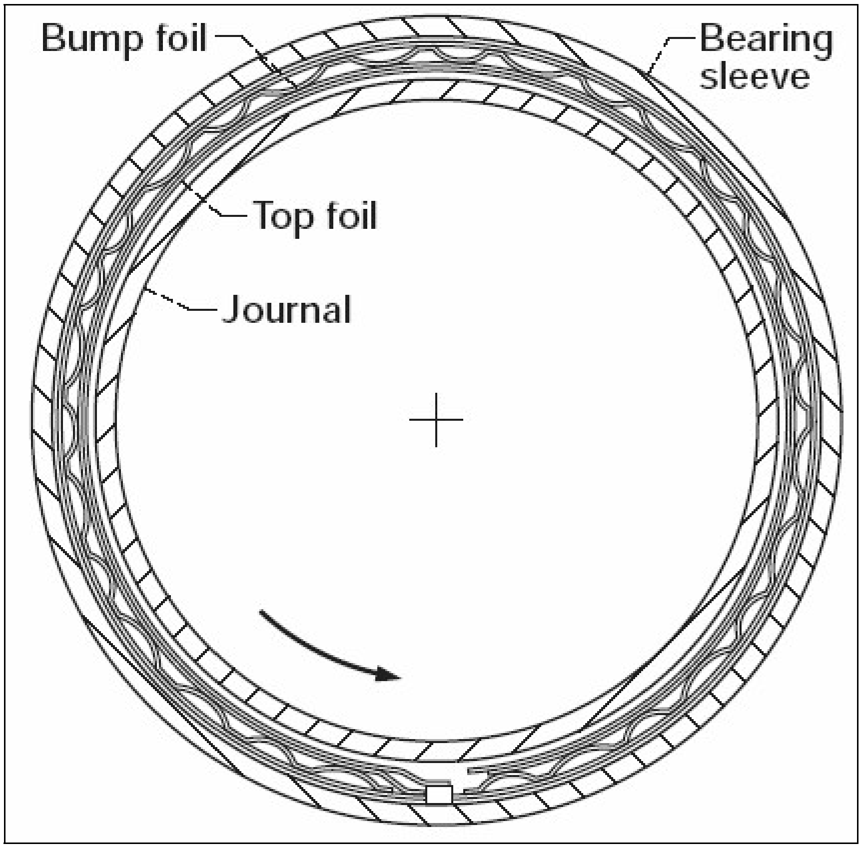


Figure 1. Cross-section of typical modern foil journal bearing.

Foil thrust bearings, diagrammed in figure 2 and pictured in figure 3, are composed of similar elements used in journal bearings, but are designed to support a shaft axially. Often, discrete compliant pads are attached circumferentially around an annular backing plate and consist of a compliant reinforcing structure supporting the flexible top foils that form the hydrodynamic film. The rotating thrust runner, diagrammed in figure 4 and pictured in figure 5, drags the viscous gas into the converging gap of each pad in a manner functionally similar to a rotating journal.

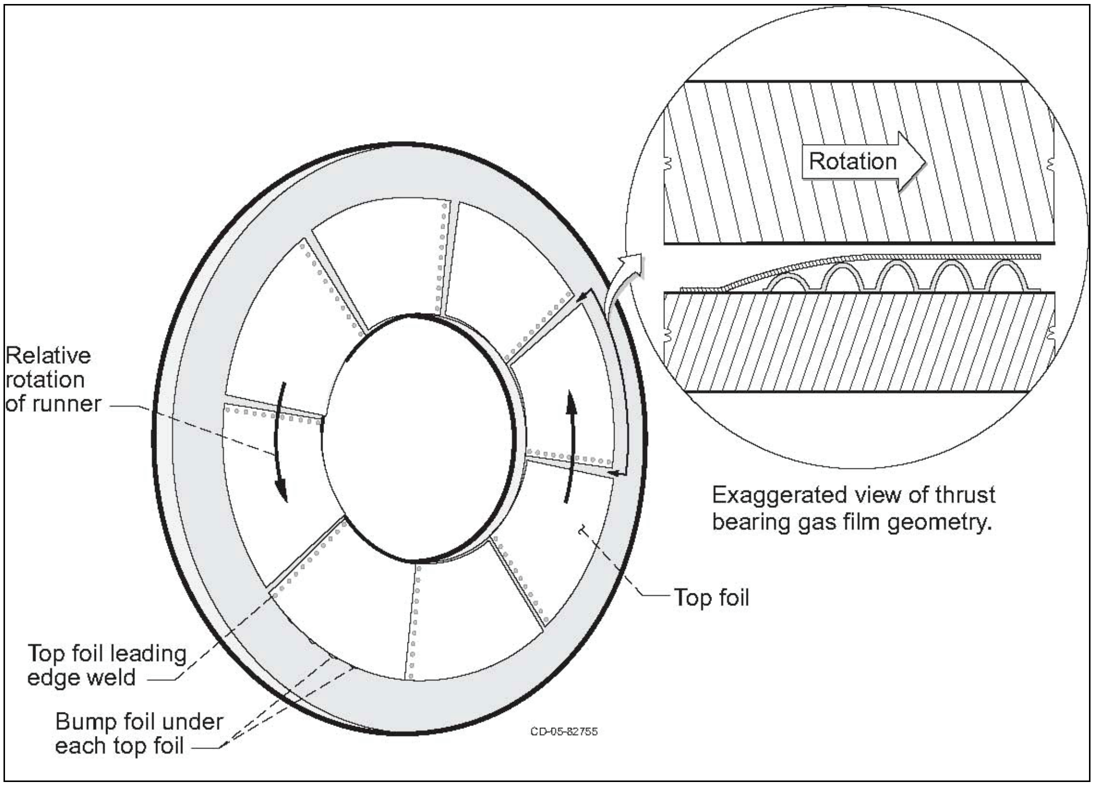


Figure 2.  Typical foil thrust bearing geometry.

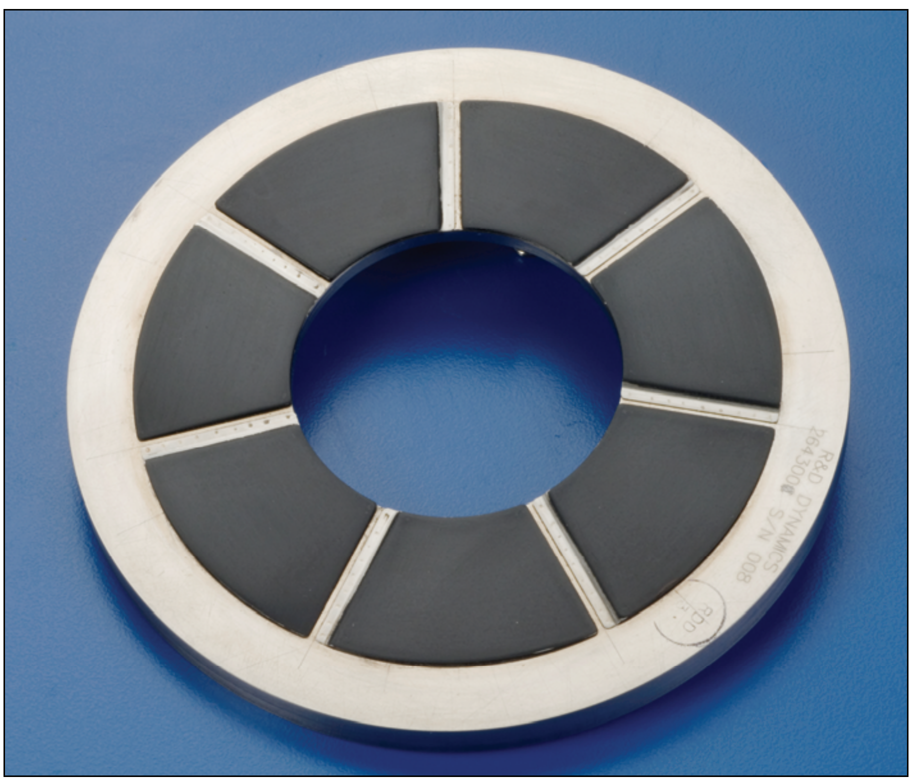

Figure 3.  Photograph of a seven pad PTFE-coated thrust bearing.

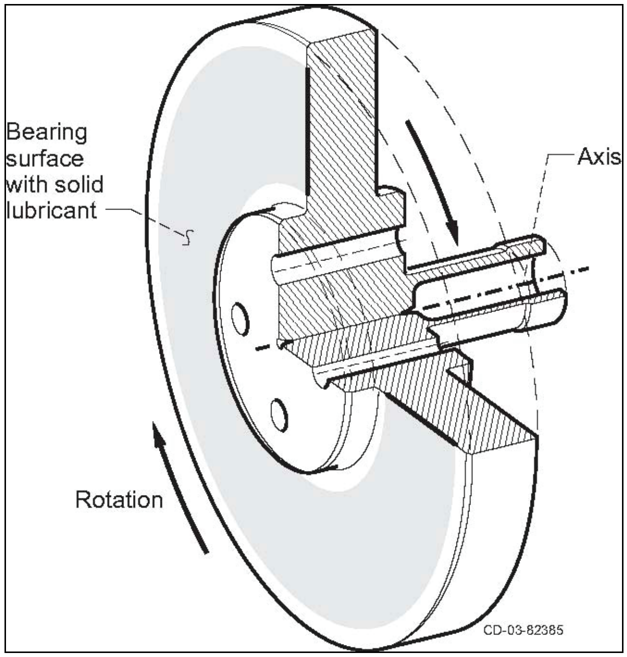


Figure 4. Diagram of a typical thrust runner specimen.

Figure 5. Photograph of a thrust runner coated with thin dense chrome.

In both thrust and journal bearings, the hydrodynamic gas film is fully formed only above a threshold speed, generally referred to as the liftoff speed. During startup and shutdown the shaft rotates below this speed, such that sliding contact occurs between the bearing and runner/journal during every start/stop cycle. Because of this, adequate solid lubrication is a critical component in oil-free foil bearing systems.

Simple foil bearings have been in commercial use since the 1970s in the air cycle machines (ACMs) used for aircraft cabin air conditioning and pressurization (*1*) due to relatively benign load capacity requirements, as well as operating temperatures within the useful range of polytetrafluoroethylene (PTFE) foil coatings. Over the past two decades however, advances in technology have produced foil bearings with improved load capacity and dynamic characteristics, solid lubricant coatings capable of tens of thousands of operations cycles at high temperatures in excess of 650 °C (1200 °F), and improved analytical and numerical tools. These technology advances have broadened the range of viable foil bearing applications to include power generators, turbochargers, and small gas turbine engines with more demanding requirements of the bearings (*2*).

Despite the advances in the design and lubrication of foil journal bearings, less research and development for foil thrust bearings has been reported in the open literature; therefore, demonstration of foil thrust bearings with adequate performance and durability for many applications remains a high priority. Although the design of advanced foil thrust bearings is left to industry, evaluation of coating systems and durability in thrust bearings is an active research area for Government researchers.

PS304, a plasma-sprayed ceramic/metallic composite solid lubricant coating developed at NASA (*3,4*), has demonstrated excellent friction and wear properties over a wide temperature range when deposited as a shaft coating for journal bearings (*5*). However, the post-deposition grinding of the PS304 surface results in an undesirably large surface roughness of $R_a$ = 0.2 - 0.8μm (8-32 μin), mostly due to the coating porosity (*2*). Because gas film thicknesses are generally in the 10-30 μm range, the roughness of the as-ground PS304 has been shown to result in reduced load capacity in foil bearings (*6,7*). As the coating is subjected to start-stop cycles with periods of sliding contact, the surface finish improves to $R_a$=0.1 or smaller, with a corresponding increase in load capacity. This effect is accelerated if the start-stop cycling is performed at elevated temperatures. Sacrificial overlay coatings to improve the surface finish and performance of PS304 at entry into service have been studied in journal bearings (*8*), and the present test rig is intended to continue these studies in thrust bearings.

The test rig described below is intended to augment foil bearing research by enabling high temperature and long duration tests to be performed on thrust bearings, simulating decades of service. Both bearing and thrust runner specimens are interchangeable with specimens that fit an existing high-speed turbine-driven test rig at NASA Glenn Research Center (*9,10*), allowing single samples to be tested over a full range of speeds after long histories of start-stop cycling.

## Test Rig Design

The Low-Speed Thrust Bearing Rig is pictured in figure 6, and diagrammed in figures 7 and 8. A thrust runner is mounted inside the test chamber to a vertically-oriented motor shaft, as shown in figure 7. A test thrust bearing is bolted to a non-rotating shaft stack that is supported radially by hydrostatic air bushings, which allows free axial and angular motion of the test thrust bearing. The test bearing shaft is restrained from rotation by a radially-extending torque arm attached to a linear variable differential transformer (LVDT) type load cell that measures test bearing reaction torque. An electrical resistance furnace lines the inside of the test chamber and is capable of heating the bearing and runner up to 540 °C (1000 °F). An electronically controlled pneumatic actuator is capable of imparting thrust loads on the test bearing up to 1000 N (225 $lb_f$).

Figure 6. Photograph of low-speed thrust bearing rig as assembled.

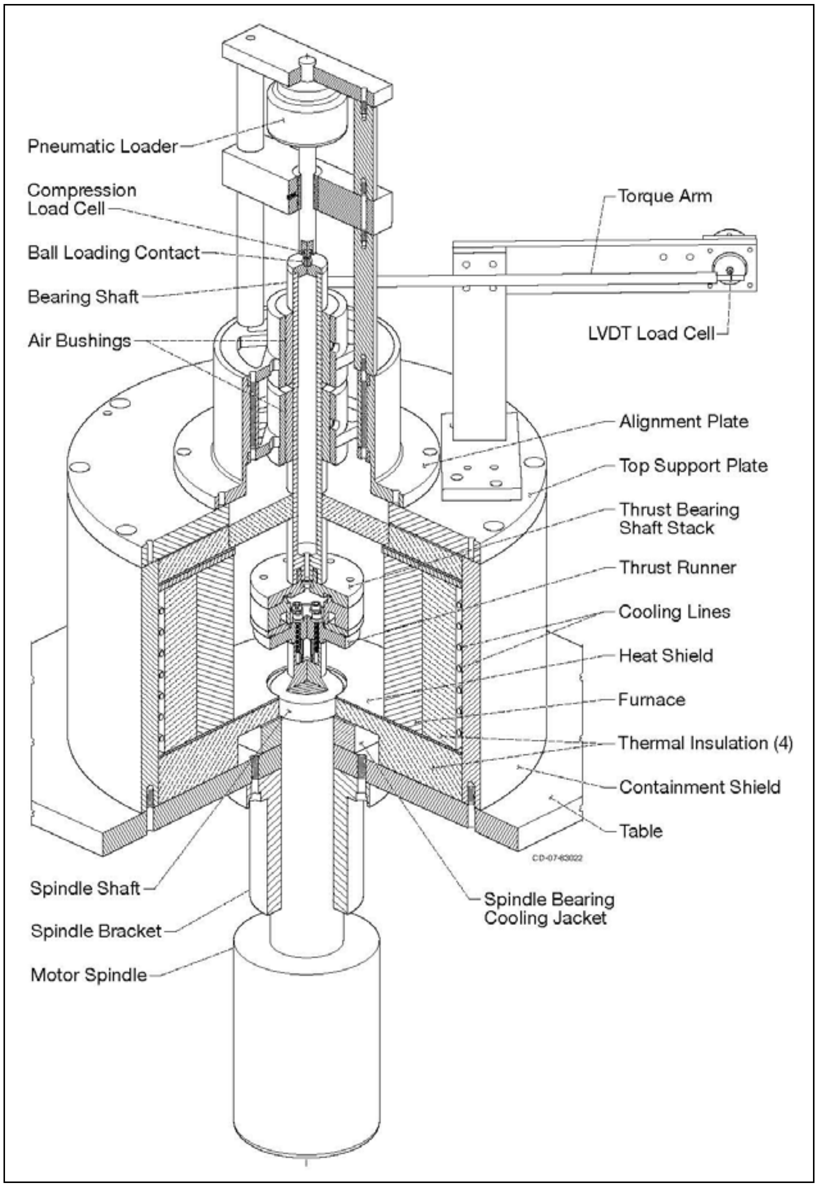


Figure 7. Section view of low-speed thrust bearing rig as assembled.

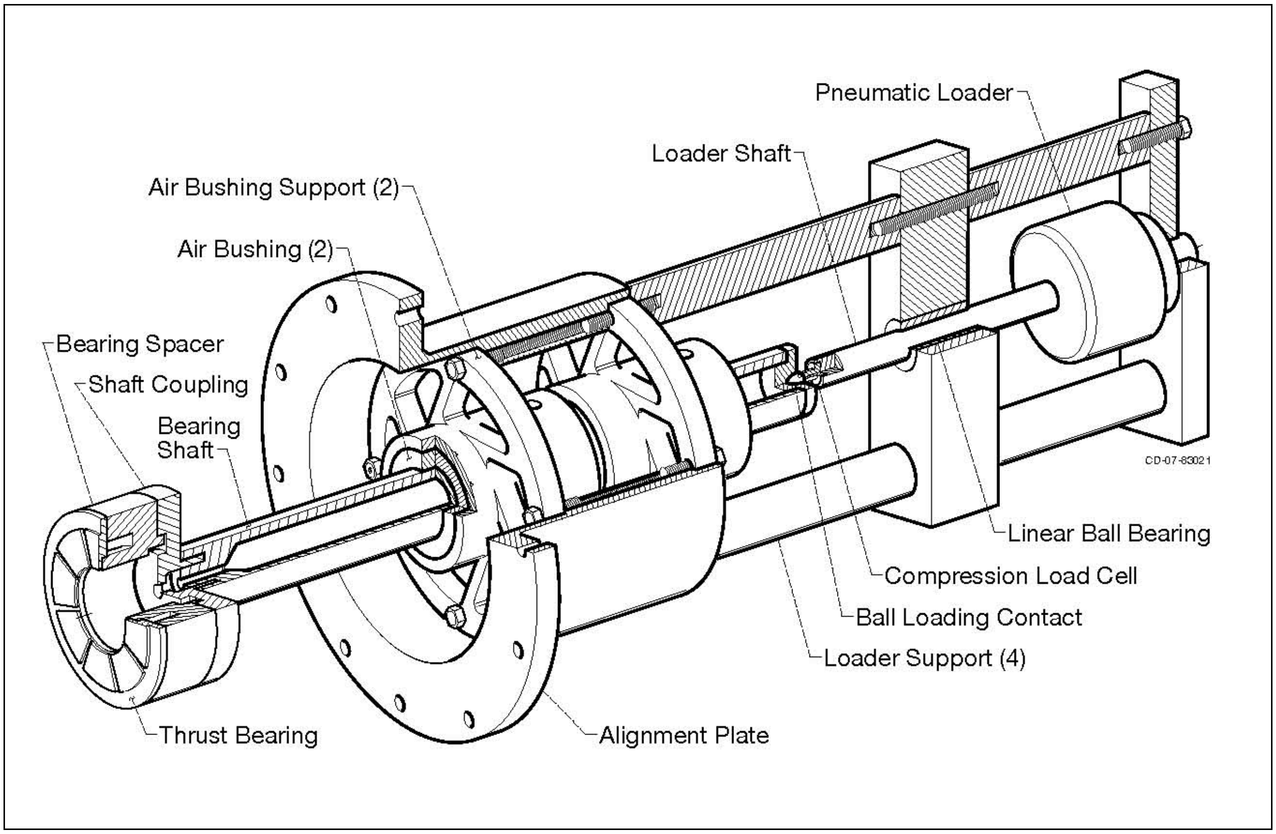


Figure 8. Diagram of removable upper rig section.

The 4.1 kW (5.5hp) motor is capable of speeds up to 21,000 rpm and is fitted with a shaft designed to mate with a test thrust runner. The runner is mounted to the shaft with four high strength bolts, and an interference fit ensures concentricity of the runner and shaft. Mating surfaces on the runner hub and shaft end are precision machined to ensure runout of the rotating test specimen surface typically remains below 10 μm (400 μin). The rotating shaft is supported by grease-lubricated precision angular contact bearings and has a fan mounted on it to cool the motor housing. The motor is clamped in a bracket and bolted to the underside of the table, with the shaft extending through the table and into the furnace. The spindle bearing cooling jacket is a water-cooled copper block clamped to the spindle just above the table, surrounding the angular bearing closest to the test chamber. This arrangement is intended to keep the bearing within the acceptable temperature range for the lubricating grease by removing some of the heat conducted down the shaft from the test chamber, as well as heat generated by friction in the bearing.

The test chamber is housed within an outer steel shroud (described in figure 7 as “containment shield”) that provides specimen burst containment and also serves as the main structural element supporting and aligning the rig top support plate. A copper cooling line is coiled around the inner wall of the containment shield to provide temperature control of the shroud, ensuring dimensional stability and preserving alignment of the test bearing and runner. A ceramic tubular furnace with resistance heating elements immediately surrounds the test chamber, and ceramic fiber insulation fills the space between the furnace core and the containment shield cooling line. The resulting test chamber has a diameter of 20 cm (8 in.) and a height of 15 cm (6 in.). The top and bottom of the test chamber are lined with high-temperature vacuum-formed alumina insulation boards. The furnace is rated to 1100 °C (2012 °F), but chamber temperatures are presently limited to 540 °C (1000 °F) due to the present cooling capacity designed into the system.

A ground top support plate rests on top of the containment shroud, and shims are placed as required to ensure the plate is parallel to the bearing surface of the runner. A support structure is attached to the top plate, and a load cell is attached to measure test bearing reactionary torque. The radial distance of the load cell from the shaft center can be changed between tests to allow improved accuracy in measurements of bearing torque both during dry sliding where torque is high, or during full-film lubrication, where running torque is comparatively low.

The removable upper rig section, shown in figure 8, supports the test bearing shaft and aligns it with the thrust runner. It bolts to the test section top plate and concentricity with the thrust runner is ensured through the use of pins. Two hydrostatic air bushings are mounted within support structures that bolt to the housing. The test bearing shaft is free to rotate and translate within the air bushings, and is hollow to limit heat conduction from the test section. A flanged shaft coupling is bolted to the bottom of the shaft and the flange surface is ground perpendicular to the shaft axis. The test bearing bolts to the coupling with an intermediate spacer, which has mating surfaces that are ground to be flat and parallel. The upper rig section and thrust bearing shaft stack are assembled with the test section, such that the contacting thrust bearing and runner are concentric and parallel. A radially extending torque arm screws into the test bearing shaft and attaches to the load cell to measure bearing reaction torque (figure 7). The minimal thrust load on the test bearing is equal to the weight of the shaft stack, generally 25 N (6 $lb_f$) or more.

For tests where variable thrust loads in excess of the shaft stack weight are required, an electronically controlled pneumatic actuator is installed on a rigid structure attached to, and extending above, the upper housing. The pneumatic actuator transmits force through a 16 mm (0.63 in.) diameter shaft that is aligned with the test bearing shaft through a linear rotary bearing. A small compression load cell attaches to the shaft and pushes on a ball contact that is mounted to the test bearing shaft. This permits application of large axial forces with little transmission of rotary torque.

A variable frequency drive powers the spindle and is capable of external speed control and widely variable acceleration rates. A braking resistor attached to the drive is able to stop the spindle quickly through dynamic braking of the shaft rotational energy. This spindle arrangement has significantly more speed control repeatability than impulse turbine-driven test rigs operating with compressed air. The tightly controlled and repeatable speed trace reduces scatter in the startup and shutdown torque maxima.

Thermal management of various components is achieved using a combination of air- and water-cooling. Cooling air is supplied to the air bushings and test bearing shaft when required by test conditions. Water is used to cool the forward spindle bearing and chamber shroud, as previously described. Flow rates for cooling water and shop air are variable and controlled through a combination of regulators and valves, while inline rotameters allow flow rates to be set accurately. Thermocouples mounted on structural components are used to monitor temperatures in critical locations and verify that adequate cooling flows are being applied.

Control and data acquisition functions are both performed by a programmable automation controller consisting of a real-time processor and attached signal input and output modules. All electronics and data acquisition equipment are located in a rig-adjacent instrument panel, with monitoring, control, and data logging performed remotely via network connection. Shutdown logic is resident on the controller in the event of a communication failure. Health monitoring signals include speed, reaction torque, applied load, vibration levels, and various temperatures, where exceeding a preset limit on any signal will initiate shutdowns of the motor and furnace and remove the actuated thrust load.

Two modes of operation include start/stop speed cycling and manual operation. Both modes contain a common shutdown logic and data logging scheme, and data displays are similar. In cycling mode, the operator can vary cycle timing and speed parameters as the test requires and test bearing parameters are logged at a user-specified rate. Applied thrust load can be varied during the test if desired. In manual mode, the speed and load are user-controlled to allow for the measurement of bearing torque and power loss at various operating conditions. Load capacity and other bearing attributes can also be measured using this mode.

Uninterruptible power supplies protect the remote computer, real-time control module, and instrumentation from short interruptions of electrical power. Controller-resident real-time health monitoring and shutdown logic ensures safe unattended operation with tolerance to electrical power interruptions and communication faults.

## Test Articles

Thrust runners, shown in figures 4 and 5, are rotating disks usually constructed of Inconel 718, a nickel-based superalloy with desirable high-temperature strength and creep resistance properties. A typical runner has a flat bearing surface extending to an outer diameter of 10.2 cm (4.0 in.) and an inner hub containing a cylindrical locating feature, which minimizes runout when bolted to a rotating shaft. The bearing surface is ground flat within 5 μm (200 μin) and mechanical runout is typically kept under 10 μm (400 μin) at the outermost radius. Runners can be balanced to within 0.72 g*mm (0.001oz-in) to allow testing up to 80,000 rpm on a separate test rig (*9*), although less stringent balance levels are permitted for tests at lower speeds. For low-to-moderate temperature tests, thrust runners may also be constructed of 17-4 PH or other suitable alloy steel.

Depending on intended operational temperatures, many solid lubricant coatings are available for application to the thrust runner. Typically a hard coating is used on the rotating surface, with a comparatively soft coating applied to the stationary bearing top foils. For low to moderate temperatures, a thin dense chrome coating up to 10 μm (400 μin) thick is popularly used on the journals and runners for its good friction and wear properties and smooth finish. For higher temperatures, PS300-series lubricants can be used to achieve good friction and wear properties after an initial conditioning of the coating surface that lowers its roughness. Sacrificial "break-in" coatings are typically applied to PS300-series coatings to achieve better surface finish and performance at service entry (*8*).

Thrust bearings, shown in figures 2 and 3, are generally purchased from several commercial manufacturers, although some are fabricated at NASA Glenn (*11*). As previously described, they generally consist of a rigid backing plate to which a number of discrete arcuate pads are attached. Depending on intended operating conditions, the backing plate can be constructed of various corrosion-resistant steels, and bearing foils are most often constructed from Inconel X750.

Commercial bearings are purchased with various available top foil solid lubricant coatings such as PTFE, polyimide, and proprietary formulations such as those described by Heshmat et al. (*12*). Historically, PTFE-based coatings have been popular for their low friction behavior and temperature capability up to 260 °C (500 °F), but coatings with increased temperature capability are required for some applications. Uncoated Inconel X750 top foils run against PS304-coatings in journal bearings have proven effective in high temperature applications (*8*); accordingly the performance and durability of uncoated thrust bearings are being evaluated due to the comparatively short wear life of polymer-based coatings.

Test article surfaces are often characterized off-rig to measure relevant parameters such as surface roughness and wear volumes. Both stylus-type contacting profilometry and non-contact interferometric profilometry are used to measure surface characteristics of the runner and top foils. Surface measurements are conducted prior to and after test bearing operation to study wear and surface morphology.

## Experimental Testing

A two thousand start/stop cycle test was performed at 430 °C (800 °F) and is presented as an evaluation of test rig capabilities. A six-pad uncoated thrust bearing with geometry described by Dykas et al. (*11*) was run against an as-ground PS304-coated thrust runner to verify high-temperature endurance of the bearing and coating. Cycles lasting approximately fifteen seconds each are run to a maximum speed of 20,000 rpm, with an applied thrust load equivalent to approximately 7 kPa (1 psi) when divided by the top foil area. A typical cycle trace of nondimensional torque and speed is shown in figure 9. Measured torque has been nondimensionalized by the applied thrust load multiplied by the arithmetic average of the inner and outer top foil radii, according to:

$$T' = \frac{2T}{W(r_o + r_i)},$$

where:

T′ = nondimensional torque

T = measured torque, N·mm (in·lb)

W = thrust load, N ($lb_f$)

$r_o$ = top foil outer radius, mm (in.)

$r_i$ = top foil inner radius, mm (in.)

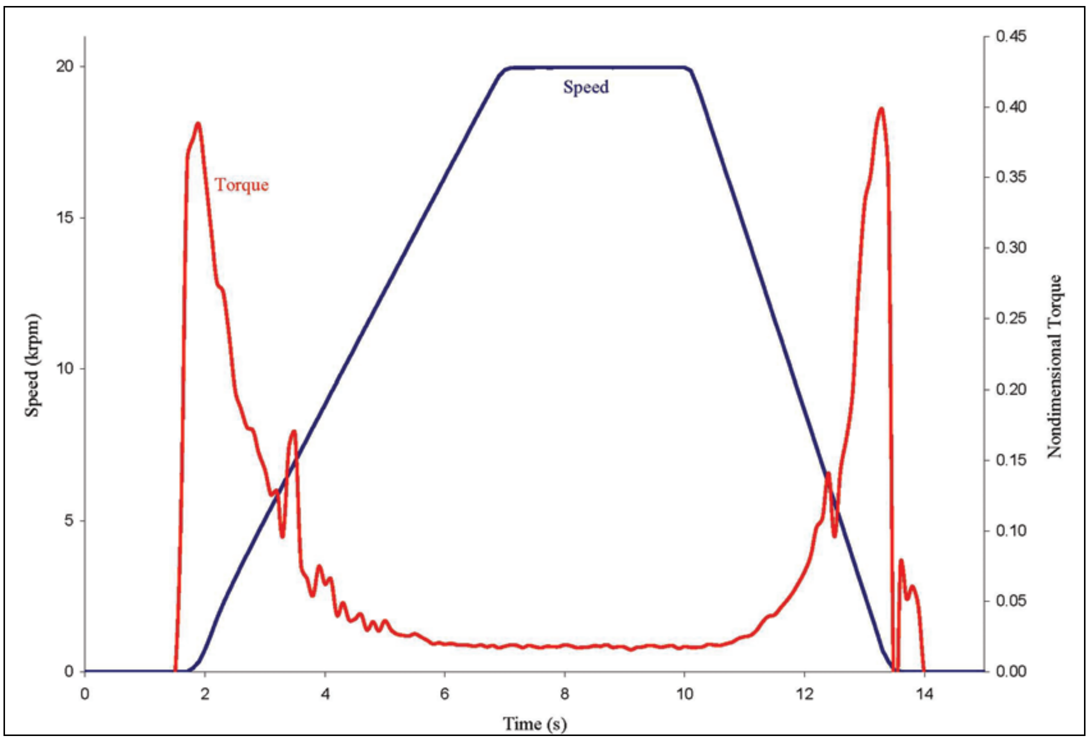


Figure 9. Typical time trace of speed and torque during start-stop cycle – average of five cycles.

The cycle consists of a short dwell time at rest, followed by a constant acceleration to full speed, a short time at full speed, and a constant deceleration back to rest. In that time, the nondimensional torque rises to a peak value indicative of the static friction coefficient between the runner and bearing, followed by a decrease as slip occurs between the two surfaces, and a continued decrease as the bearing transitions to mixed lubrication and finally to a full hydrodynamic gas film. The nondimensional torque at full operating speed shows the low viscous drag of the gas film compared to dry sliding friction. As speed is decreased, the tribological behavior of the bearing progresses in reverse order to sliding contact, with a resulting torque maximum during shutdown.

Prior to the high temperature cycling, the PS304 surface roughness is measured to be $R_a = 0.85$ μm (33 μin), in agreement with as-ground PS304 coated journals as reported by Radil and DellaCorte (*6*). After two thousand start/stop cycles, the PS304 coated runner surface roughness is reduced to $R_a = 0.36$ μm (14 μin). Although the roughness measured after the test shows significant improvement, it remains high compared to that measured on fully conditioned PS304 journals reported in the literature. From this measured roughness and visual inspection of the test articles, two thousand cycles at 430 °C (800 °F) and 7 kPa (1 psi) of applied load do not appear to be sufficient to fully condition the PS304 surface to minimize roughness and maximize load capacity. However, this test provides evidence that the test rig is able to perform durability testing of foil thrust bearings with candidate solid lubricant coating systems.

It is notable that this abbreviated bearing durability test takes place at a lower temperature than the rated 540 °C (1000 °F) maximum temperature of the test rig. Initial tests at the maximum temperature experienced compromised torque measurements resulting from light contact between the test bearing shaft and the lower hydrostatic bushing due to thermal expansion. Although subsequent minor modifications to directed cooling air flow and shaft dimensions were successful in restoring the full temperature range of the test rig, the 430 °C (800 °F) coating durability test is left as sufficient evidence of acceptable test rig operation at elevated temperature.

## Concluding Remarks

The test rig described herein augments existing test capabilities in oil-free thrust bearing research. The primary purpose of this facility is to subject a bearing and thrust runner to high-temperature repeated start/stop cycles for evaluation of performance and durability over a simulated machine lifetime. However, it is also possible to measure bearing torque and power loss at steady operating conditions, and can be used to determine bearing load capacity.

Friction and wear of the solid lubricant systems, bearing load capacity, and running torque from hydrodynamic shear can be measured at periodic intervals and used to guide integration of foil thrust bearings into candidate systems. Wear mechanisms and bearing failure modes can also provide valuable information supporting improvements in design. It is anticipated that the test rig and the enhanced test capabilities it offers will assist in the future development of thrust foil bearings and their application to advanced Oil-Free Turbomachinery systems.

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